Improvement of Robustness in Grid Connected Solar System Using Artificial Neural Network based Sliding Mode Controller

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Abstract — In Renewable energy schemes, Solar photovoltaic (PV) systems provide effective incorporation of generating electrical energy. Many current control techniques such as Hysteresis control, predictive control and Sliding mode control are available to improve the performance of PV systems. However, the current tracking of the existing controllers is suffered when connected to the grid-connected system due to the lack of constant switching frequency in the three-phase inverter control. Furthermore, the complexity of these systems is very high. An Artificial Neural Network (ANN) based Sliding Mode Control approach has been used to solve the voltage regulation in the grid-connected solar system. This model has been employed to implement a two-loop controller using a voltage controller as an outer loop and a current controller as an inner loop. The ANN- SMC-based three-phase inverter is simulated to diminish the load current's harmonics and provide robustness in the inverter control. The proposed system results show the robustness improvement of the grid-connected solar system with a low level of Total Harmonic Distortion (THD).

Keywords- *ANN-based Sliding Mode Control, Solar PV, Total Harmonic Distortion, two-loop controller.*

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I. Introduction

A PV structure is accomplished to transmit power to a specific load by openly varying solar energy over the PV effect. The system structure is very adaptable. PV units are the leading construction blocks; these can be organized into arrays to increase the production of electric energy [1]. Generally, extra equipment is mandatory to transform energy into a convenient form or store energy for additional usage. The following scheme will determine the energy necessities (or loads) in a precise application [2].

Electricity produced from PV structures is vital renewable energy, which encloses zero greenhouse gas emission and no fossil fuel consumption [3]. A 60% average annual progress rate of PV capacity was seen from 2004-2009, and an 80%–90% development was estimated in 2011. Extremely reliable PV systems, as a result, will meaningfully increase non-conventional output, assures a more significant profit on savings, and support curtailing carbon emissions universally [4]. Like any other electrical structures, PV systems linked to a grid can be unsuccessful due to accidental events and infrequent failures in their modules after considerable financial loss [5]. The reliability of the PV system, which was linked to an electrical grid, has been of excessive concern to both utility companies and customers [6]. Usually, a PV structure is collected from numerous vulnerable modules [7], like power electronic devices and PV cells [8], whose lifecycle reliability relies tremendously on loads besides ambient situations.

The issue regarding the optimal regulation of the inverter connected to a grid has been analyzed [9]. Initially, the discrete-time non-linear mathematical model of a single phase PV

inverter, which was linked to a grid in the rotating coordinate system, was fabricated through a delta operator.

It simplified a process of regulation and then enabled digital realization directly. Furthermore, an optimum control technique has been developed to attain trajectory PV tracking for inverters associated with the grid. More prominently, the performance controller matrix, which was significant to several system performance indicators, also enhanced by the particle swarm optimization. A standalone system is generally adopted with a battery for storing energy, and control of such frameworks is very complex when in contrast with the grid-connected systems [10].

For today's electricity demand, standalone PV systems are not an absolute way to satisfy the power requirement; a significant quantity of PV energy must be associated with the grid [11]. The grid coordination provides the maximum amount of PV power with a unity power factor and minimum THD value to the grid, which is transferred to the highly efficient power electronic converters, commonly choppers or inverters. Control of such PV inverters is complex, like independent PV inverters [12]. High current controllers are required for these inverters to follow the current reference precisely and to lessen the current harmonics to guarantee the secure operation of the entire framework. The most popular controllers like hysteresis and predictive current controller procedures are utilized for PV inverters [13-14]. In hysteresis control, constant switching frequency expands the complexity of the execution. Predictive control gives consistent switching frequency but requires precise data on the circuit parameters.

However, the performance of these existing grid-connected three-phase PV systems is poor compared with the operation of the single-phase PV system. This is due to process synchronization problems and the variation in the source and load side of the PV system. This article suggests a sliding mode control technique for robustness improvement in the proposed grid-connected PV system. The main contribution of this article is the reduction of Total Harmonic Distortion at the load side of the grid-connected solar system[15,16-40].

The primary purpose of this system is to provide a sliding mode controller for grid-connected PV system with maximum precision in the control of grid current and minimized harmonic current distortion. The ANN-based SMC controller has been used instead of the PI controller for tuning the control parameters of the three-phase inverter. The results specify that the proposed approach has higher performance in robustness operation of the grid-connected PV system compared to existing control methods. The organization of this article is as follows: Section 2 details about proposed system; Section 3 describes results and discussions, conclusion and future work in Section 4.

II. METHODOLOGY

Solar Photovoltaic (PV)

The advancement of solar photovoltaic is mainly used nowadays. The characteristics of all PV panels depend on the temperature and solar irradiation. Solar PV typically involves boost converter, which convert fluctuating DC into constant DC and inverter converts' constant DC value into DC value, which is well-matched through the associated AC loads. The system parameter like the inverter output voltage and DC-link voltage may vary as the output parameter along with the input parameter, i.e., radiation of sun and heat will change, which is not needed and accepted [15]. PV-cell is equipment, which converts sunlight into electricity. PV systems consist of many cells, such as panels and arrays. The PV plants are used for electricity generation supplied to the grid and load. The electricity produced is stored, utilized directly for self-consumption, or provided to massive power grids. Interconnections of panel or array estimate the value of output, current or power; also, it is a variable contingent on the sunlight. Energy storage structure is a significant factor for balancing the system or energy management [16].

The following equations express the functioning of a solar cell concerning voltage of the cell to the current [17-18].

$$V_{PV} = \frac{ATK}{q} \ln\left(\frac{Iph - Ipv + Io}{Io}\right) - IpvRs \tag{1}$$

$$I_{PV} = I_{ph} - I_O[\exp(\frac{q(v + I_{pv}R_s)}{AKT}) - 1] \tag{2}$$

$$Iph = [Iscr + Ki(T - 298)]\lambda / 100 \quad (3)$$

$$I_O = I_{or} (\frac{T}{T_r})^3 \exp[\frac{qE_{\partial}}{BK} (\frac{1}{T_r} - \frac{1}{T})] \quad (4)$$

Where,

I_{pv}= Output current (A);

V_{pv} = Terminal voltage (V);

l_{pv} = light-generated current (A);

I_o = saturation current (A).

A=B Ideality factor (1.60);

Q= Electron charge ($1.6x10^{-19}$ C);

I_{or} = saturation current at T_r ($2.0793x10^{-6}$);

T_r = Reference temperature (301.10 ^{o}K);

E_{GO} = Band gap for silicon (1.10 eV).

T= PV cell temperature (^{o} K);

K=Boltzmann's constant ($1.380x10^{-23}$ Nm/^{o} K);

K_i = Short circuit current temperature coefficient at I_{scr} (0.0017 A/^{o} C);

λ = illumination (mW/cm^2).

Equation (2) represents the generation of the solar PV system. In this paper, the grid-connected operation of the solar system is used.

Artificial Neural Network (ANN) Controller

Artificial neural network (ANN) is similar to human brain, which has been designed to analyze and process information. An ANN consists of computational units identical to the neurons of the biological nervous system known as artificial neurons [19]. The ANN model comprise of input, hidden, and output layers. The perceptron is an uncomplicated structure of a neural network, having a single neuron with changeable synaptic weights. This network has single input layer, which projects on to an output layer of neurons. Moreover, the neurons in this network always move in the forward direction, so they are known as feed-forward networks. This single layer cannot give an accurate output while applied to solve the problem. The number of layers has been increased to get a precise result [20]. Such a network is called as a multilayer perceptron feed-forward neural network, and its block diagram of ANN is shown in Fig.1.

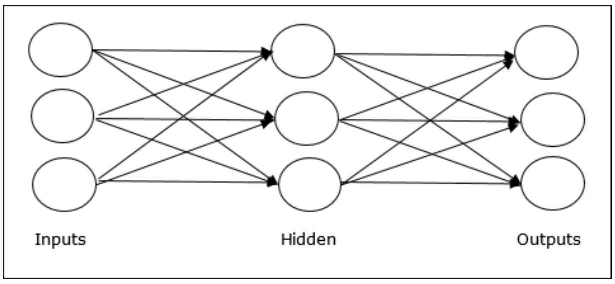

Fig 1 Block diagram of ANN.

Sliding Mode Controller (SMC)

The SMC employs a time fluctuating state-input discontinuous control law, which made to switches at high frequency starting with one persistent arrangement and then onto the next, as indicated by the current position of state factors in state space [21]. The aim is to drive the framework's elements under control to go after what is wanted. SMC is incredibly fascinating because its known qualities of robustness and framework order decrease the ON-OFF contact of power switches. A standout amongst the most critical highlights of the sliding mode routine in factor structure frameworks is the capacity to accomplish reactions that are autonomous of the framework parameters. The simple execution of SM control through the hysteresis band does not require extra calculation or assistant hardware. There are fundamentally three methodologies for keeping the switching frequency of the sliding mode controller consistent [22].

(a) Constant incline or timing capacities precisely fit into the controller. In this control plot, the settled switching frequency under every single working condition are controlled through changing the slope/timing capacity. (b) Adaptive control into the sliding mode controller to neutralize the variation of switching frequency. The existence, reaching and stability conditions should be fulfilled to ensure the stability of an SMC.

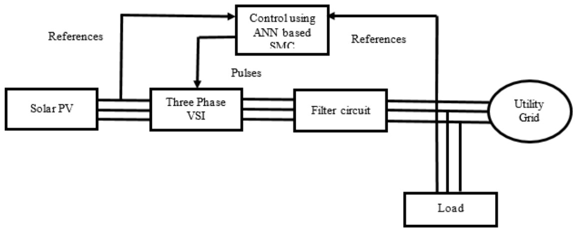

Fig 2 Architecture of the proposed system.

The Existence condition guarantees the structure, which can fall in the sliding surface area [23-24,40-56]. The reaching condition safeguards the system by representing a point, which can ultimately touch the sliding surface beginning from anywhere in state space. Stability condition ensures the structure is kept on a sliding surface.

III. PROPOSED METHODOLOGY

In this proposed technique, performance of grid-connected PV system is improved by using an ANN-based sliding mode controller. Furthermore, the real and reactive power has also improved by using this proposed ANN-based SMC. The power generation from the PV array is DC. This generated power is converted into AC and connected to utility grid using a three-phase inverter. LC filter is employed to reduce the ripples of the inverter output waveform. In grid-connected systems, grid synchronization is essential. The pulse generation of the inverter depends on the coordination of grid voltage and load current. The voltage across the DC terminal of the inverter is taken as a reactive power constraint and compared with the constant voltage.

The architecture of the proposed system is illustrated in fig.2, which uses ANN-based SMC controller to regulate line current in the variable reference frame over the generations of similar reference voltage vectors. The purpose of the framework controller is to obtain voltage regulation of the inverter. In SMC working point travels through the inside of the sliding surface, which is accomplished with control inputs. Hence choosing the suitable Sliding Surface (SSF) is an initial phase in planning the controller.

Choosing the sliding surface

$\sigma(x,t) = 0$ (reference current – grid current =0)

Equivalent control input V_{eq} is determined using invariance condition,

$\sigma(x,t) = 0$ and $\dot{\sigma}(x,t) = 0$. with $V(t) = V_{eq}$.The equivalent control $V_{eq} i(t)$ keeps operating point within sliding surface $\sigma(x,t) = 0$.

Non-linear switching input V_{nom} was attained using Lyapunov stability criteria, i.e. $\sigma\dot{\sigma} < 0$.

The sliding surface is given by,

$$\sigma(x,t) = I_{grid,a} - I_{ref} \tag{5}$$

The power supplied to the grid is given by,

$$P_{grid} = V_{grid,a}(t) I_{grid,a} + \left(I_{grid,a}\right)^2 . R \tag{6}$$

Assume negligible resistance R≈0,

$$P_{grid} = V_{grid,a}(t) I_{grid,a} \tag{7}$$

Where,

$$I_{grid,a} = I_{grid,a\_pk} sin\omega t \tag{8}$$

$$V_{grid,a}(t) = V_{EP} sin\omega t \tag{9}$$

Substitute (8) & (9) in (7)

$$P_{grid} = V_{grid,a}(t) * I_{grid,a} = V_{EP} I_{grid,a\_pk} sin^2\omega t \tag{10}$$

$$= V_{EP} I_{grid,a\_pk}(1 - cos2\omega t)/2 \tag{11}$$

Where ,

I_{grid,a_pk}= A phase grid peak current;

V_{EP}= peak of $V_{grid,a}(t)$.

Average grid power is obtained as,

$$P_{grid\_avg} = \frac{2}{T} \int \left(V_{EP} I_{grid,a\_pk}(1 - cos2\omega t)/2 \right) dt \tag{12}$$

$$= V_{EP} I_{grid,a\_pk}/2 \tag{13}$$

Assume lossless power transmission from inverter input to grid,

$$P_{dc\_avg} = P_{grid\_avg} = V_{EP} I_{grid,a\_pk}/2 \tag{14}$$

Using (14)

$$I_{grid,a\_pk} = 2P_{dc_{avg}}/V_{EP} \tag{15}$$

Reference current becomes,

$$I_{ref} = 2P_{dc_{avg}} sin\omega t/V_{EP} \tag{16}$$

$$I_{ref} = I_{grid,a}{}^* = I_{grid,b}{}^* = I_{grid,c}{}^* \tag{17}$$

Then set a control input for sliding mode operation to configure the system:

$$V(t) = V_{eq}(t) + V_{non}(t) \quad (18)$$

Where $V_{eq}(t)$ an equivalent control is input, which regulates system's behaviour and $V_{non}(t)$ is a non-linear switching input that maintains state on a sliding surface in presence of dissimilarities and disturbances.

The invariance condition is used to get the $V_{eq}(t)$.

$$I_{grid\_a} = \int\left(\left[V_{dc}V(t) - R.I_{grid_a} - V_{grid_a}(t)\right]V_{EP}/L_n\right) + \eta \quad (19)$$

Where,

η — noise and measurement error.

$$L_n = L_a + L_b + L_c \quad (20)$$

From (5), (16) and (19),

$$\sigma(x,t) = \frac{\left[\left(V_{dc}V_{eq}(t) - R.I_{grid_a} - V_{grid_a}(t)\right)\right]}{L_n} - \frac{2P_{dc\_avg}\cos\omega t}{V_{EP}} = 0 \quad (21)$$

Correspondent control input is set as,

$$V_{eq}(t) = \frac{\left(R.I_{grid_a} + V_{grid_a}(t) + 2P_{dc\_avg}L_n\omega t\right)/V_{EP}}{V_{dc}} \quad (22)$$

The proposed SMC reduces these effects by using its reverse control process. Thus, the switching frequency is always maintained constant without any additional control. Furthermore, in the proposed SMC, the sliding variables start from zero and the control is developed so that sliding condition is still satisfied. This will eliminate the reaching phase of the SMC.

IV. RESULTS AND DISCUSSIONS

In this method, the system's performance is analyzed with variation in load and source. When the irradiance is low, the power generation from solar PV is reduced. Fig.3 shows the simulation model of a 50KWPV system linked to an electrical grid with an SMC. This system is associated with R, RL and inductive load. The grid voltage V_{abc}, is taken for the grid synchronization operation, and its phase angle is measured by the Phased Locked Loop (PLL). Similarly, the inverter current I_{abc} is measured and using Parks' transformation, the I_d and I_q values are calculated. Then these I_d and I_q values are compared with their respective reference values, which are converted into abc quantities using inverse Park's transformation. Then a hysteresis controller is used to limit the values of the current. Then this parameter is compared with normal sine reference magnitude and utilized to produce the pulses of inverter. So, whatever the grid voltage and load current changes, the inverter will supply the based on the changes using pulse generation.

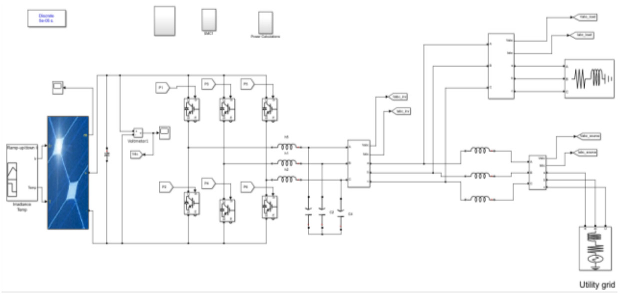

Fig 3 Simulation Diagram of the proposed system.

A non-linear load (3 phase diode bridge converter) is connected at PCC and tested at the proposed controller's output. Parameters used for simulation are Vdc=440V, f =50hz, R=6Ω, fs =11Khz, La =18.5mH, I_{ref} is varied from 6A to 5A, per phase grid voltage is 110V. For PV array Voc =300V and I_{sc}=8.2A. In the proposed methodology, to maintain the DC voltage at inverter DC terminal, an ANN-based sliding mode controller is proposed. The voltage across the V_{dc} capacitor is calculated and compared with the standard voltage. Subsequently this error and change in error is also taken by considering the derivative of the error value. This value is given as an input to the SMC, and by using the signum function, the sliding variables are maintained at the sliding surface. This will ensure the I_q reference value is calculated, whatever the V_{dc} is due to the change in load and the source variation. This increases the robustness of the grid-connected solar system. The I_q reference is related to controlling reactive power of power system and also compensated by using the proposed SMC-based controller. When the load is non-linear, i.e. inductive loads, the current lags with the voltage, which will increase the consumption of reactive power in a grid-connected system. The capacitor across the

inverter DC terminal is used to supply the required compensation. The capacitor across the inverter DC terminal is used to supply the required compensation in this situation. The sliding mode controller's total control input V(t) is found by substituting circuit parameter values in equation (23).

$$V(t) = 0.0120 I_L sin\omega t + 0.25 sin\omega t + 0.02 I_{ref} cos\omega t - 3sgn\,(\sigma) \qquad (23)$$

Eqn (23) is implemented in MATLAB Simulink, and the simulated sliding mode controller is illustrated in fig 4.

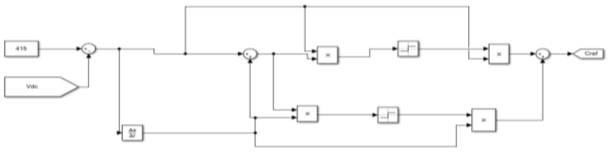

Fig 4 Proposed ANN-SMC.

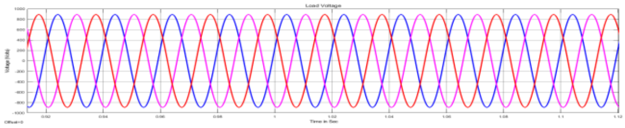

Fig 5 Load voltage.

The fig.5 and fig.6 show the output waveform of the load voltage and current. It is understood that proposed SMC-based controller maintains the sinusoidal voltage and current at load side. Proposed system is tested with resistive as well as inductive loads. Both the R and L load of the proposed system achieved sinusoidal outputs, which will increase the reliability of grid-connected solar systems. When connecting the inductive load, the load current varies. The SMC controller will quickly track it by calculating the I_q reference and the pulses generated to compensate for these changes.

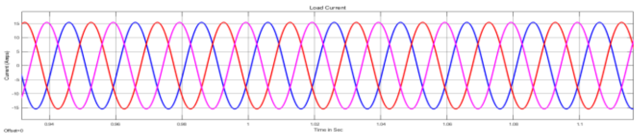

Fig 6 Load current.

Performance of this proposed technique is experimented with a variation in loads. Fig.7 shows the load voltage when the load is increased. Initially, an RL load of 14 KW is connected. At time t=1 sec, 10KW is added with the help of the breaker circuit. The increase in load allows voltage to decrease, as shown in fig.6.Then at time=3 sec, the additional load is disconnected, and now the system is operating with 14KW.

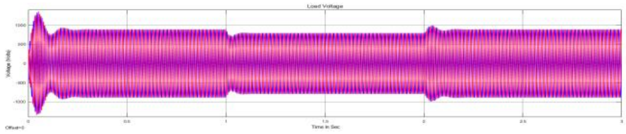

Fig 7 Output voltage when no change in load.

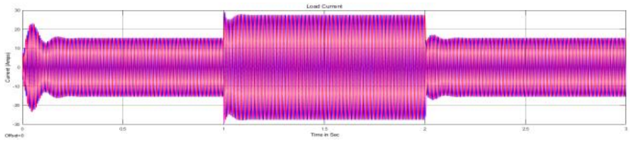

Fig 8 Output current when there is a change in load.

Similarly, fig.8 shows the output current waveform during the load variation condition. Increasing the load will increase the current amplitude. So, at 1 sec, an additional load is connected, and the current is increased. After t=2 sec, the extra load is disconnected, and the current waveform is at the normal stage. From fig.8 and fig.9 prove that the variation in the load side sinusoidal waveform is obtained in both voltage and current waveform. The proposed ANN-based SMC controller effectively tracks the changes in the voltage and current due to the load variations.

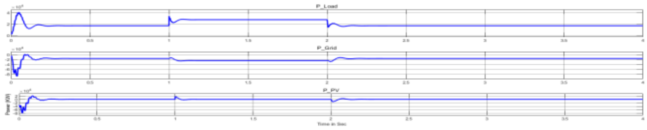

Fig 9 Real power variation when there is a change in load.

The fig.9 and fig.10 display the real and reactive power of grid-connected solar system with a change in load conditions, respectively. At time t=1 sec, the load is varied. At that time, the excess power taken by the load is delivered by the grid. It is done by tracking the grid voltage and load current. At time t=1 sec, due to load variation, the system starts oscillation. The SMC is used to track reference signal for compensating the voltage and current of the overall system. This will improve system reliability.

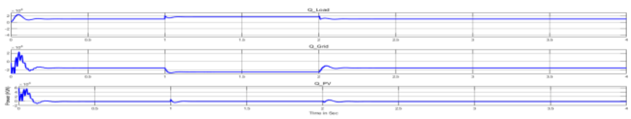

Fig 10 Reactive power variation when there is a change in load.

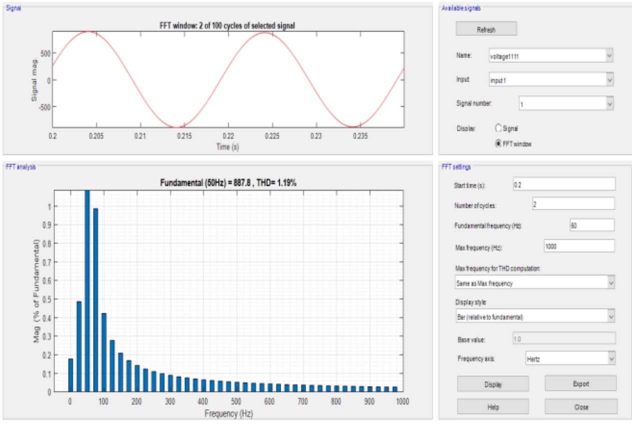

Fig 11 THD analysis.

Fig.11 illustrates THD study of the grid-connected solar system with an LCL filter. From the proposed SMC controller, a 1.19% level of THD is attained on the load side, proving the proposed system's efficacy.

EXPERIMENTAL SETUP

The hardware kit connected with the solar panel employs a maximum power point tracking process and Adaptive Neuro Fuzzy Inference System (ANFIS) control algorithm. Figure 12 shows the prototype model.

Fig 12 Prototype Model.

The experimental setup consists of the hardware kit connected with RPS in replacement with a solar panel. This is to vary the input voltage and current for the kit. The controller's duty cycle is varied and monitored on a CRO for the varying input supply.

V. CONCLUSION

In this proposed work, the robustness of grid-connected solar inverter has improved and analyzed under several load conditions using an ANN-based SMC control strategy. Voltage regulation in the grid-connected solar inverter is maintained a perfect tracking of sinusoidal current reference. The sliding surface is taken and then controlled by the output of an inverter. The consequential sliding movement is taken to obtain a model of the voltage amplitude of DC link. The result showed robustness improvement in the grid-connected solar system by providing less THD value. In future, the hybrid system with a two-loop controller will be designed to improve the hybrid wind-solar system performance when connected with the microgrid, including Battery Energy Storage Systems.

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